ECE 595
Network Economics
WNP - Chapter 2

Electrical & Computer Engineering

Outline

- Introduction to wireless communications and networking technologies
  - Radio propagation characteristics
  - Channel models for wireless communications
  - Wireless access and networking technologies
  - Radio resource management technologies in wireless networks

Wireless Communication

- Information transfer between two or more points that are not connected by an electrical conductor
- Typically: transmission of signals through free space by electromagnetic radiation of frequencies in the range of around 30 kHz to 300 GHz
- *Radio waves* are transmitted and received through *antennas*, converting electric currents into radio waves, and vice versa.
  - mobile cellular networks, wireless LAN (WiFi) systems, broadcast and television systems, global positioning system (GPS), etc.

Radio Propagation

- Transmission of radio waves from one point to another
  - either straightly and directly: line-of-sight propagation
  - or in a path affected by reflection, refraction, diffraction, absorption, polarization, and scattering
- *Line-of-sight (LOS) propagation*
  - e.g., satellite to a ground antenna, reception of television signals from a local TV transmitter.
  - the power density of a radio wave is proportional to the inverse of the square of the transmission distance.
- *Reflection:* a radio wave hits the interface between two dissimilar media → all of or at least part of the wave returns into the medium from which it originated.
  - radio wave attenuates by a factor, depending on the frequency, the angle of incidence, and the nature of the medium
  - dominant in indoor scenarios.
- *Diffraction*: propagation of radio waves bending around corners or sharp edges.
  - the diffracted radio wave is weaker than that experienced via reflection or direct transmission.
  - significant in outdoor scenarios
- *Scattering:* radio waves hit irregular objects (e.g., walls with rough surfaces)
  - the radio wave redistribute in all directions due to the reflection or refraction by the microscopic textures in the object.
  - reduced power levels

Characterization of Radio Propagation

- Three nearly independent factors:
  - distance-based path loss
  - slow log-normal shadowing
  - fast multi-path fading **small-scale propagation**

large-scale propagation

- The model of large- and small-scale propagations is called the ***channel model***.
- Having an accurate channel model is extremely important for analyzing and designing a wireless communication system

Received Signal

- When radio wave propagates, its power density diminishes gradually.
- Noise pollutes the desired signal, generating the so-called *interference*.
- The noise or interference may come from natural sources, as well as artificial sources such as the signals of other transmitters.
- Power Profile of the Received Signal

$$y = h \cdot x + \varepsilon$$

Noise: modeled as a random variable following the normal distribution (Gaussian distribution) **Gaussian noise**

The noise at different time instances is usually assumed to be identically distributed and statistically independent ➡ ***white Gaussian noise***

channel impulse response, depends on:

1. *path loss*
2. *Shadowing*
3. *multi-path propagation*

power profile of the transmitted signal

Path Loss

- *Friis transmission formula*: provides a means for predicting this received power

$$|h| = \frac{P_r}{P_t} = A \cdot \frac{\lambda^2}{d^2}$$

in dB

$$\overline{\mathrm{PL}}(d) = -10\log(|h|) = 20\log(d) - 20\log(\lambda) - 10\log(A)$$

  - λ is the wavelength
  - d is the transmission distance
  - A is a constant related to the parameters such as antenna gains, antenna losses, filter losses, etc.
- Radio waves have different propagation losses with different frequencies: lower frequency band → lower propagation loss → more suitable for long range communications, higher frequency band → short-range but high-speed wireless communications.

Shadowing

- Characterizes the deviation of the received power about the average received power.
- Occurs when a large obstruction (such as a hill or large building) obscures the main propagation path between the transmitter and the receiver.
- Effects of reflection, diffraction, scattering, etc → ***shadowing* or *shadow fading*** → formulated as a zero-mean normally (Gaussian) distributed random variable X_σ (in dB) with a standard deviation σ.

$$\mathrm{PL}(d) = \overline{\mathrm{PL}}(d) + X_\sigma = 20\log(d) - 20\log(\lambda) - 10\log(A) + X_\sigma$$

- The received power with the same distance *d* may be different, and has a log-normal distribution → *log-normal shadowing*

Multi-path

- Radio waves reaching the receiving antenna by two or more paths, due to reflection and scattering.
- Reflected waves take different paths they may have a different amplitude and phase ➡ may result in increased or decreased received power at the receiver
- Multiple versions of radio wave may arrive at the receiving antenna at different times ➡ introduce a delay spread into the radio wave ➡ interference on the successive signals: inter-symbol interference (ISI).

Wireless Multiple Access Technologies

- Allow multiple users to share the limited communication resources
- Frequency Division Multiple Access (FDMA)
- Orthogonal Frequency Division Multiple Access (OFDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)
- Random Access technologies such as Carrier Sense Multiple Access (CSMA)

FDMA & OFDMA

- FDMA: provides different frequency bands to different mobile users → allows several users to transmit at the same time by using different frequency bands
  - Second-generation (2G) cellular communication systems: Global System for Mobile Communications (GSM), where each phone call is assigned to a specific uplink channel and a specific downlink channel.
- Advanced form of FDMA is OFDMA → frequency bands are partially overlapped (but logically orthogonal), and therefore the spectrum efficiency can be greatly improved comparing with FDMA
  - Each mobile user is allowed to use one or multiple channels (more often called sub-carriers), making it flexible to provide different quality of service (QoS) guarantees to different users
  - Fourth-generation (4G) cellular communication systems, wireless local area networks (WLAN) based on the latest versions of 802.11 standards

TDMA

- TDMA is based on the time division multiplex technology, which provides different time slots to different mobile users in a cyclically repetitive frame structure.
- The whole time period is divided into multiple time slots, each for a particular mobile user.
- The users transmit in rapid succession, one after the other, each using its own time slot.
  - Second-generation (2G) cellular communication systems, e.g., GSM: based on the combination of TDMA and FDMA, where each frequency channel is divided into multiple time slots, each carrying one phone call or signaling data.

CDMA

- CDMA is based on the *spread spectrum* technology, which allows several mobile users to send information simultaneously over a single frequency channel.
- Assigns each user a different *spreading code*, based on which the signals of multiple users can be separated.
    - Direct sequence spread spectrum (DS-CDMA): third-generation (3G) cellular communication systems. Each information bit (of a mobile user) is spread to a long code sequence of several pulses, called chips. Such a code sequence is usually referred to as the *spreading code*.
- The separation of the signals of multiple users is made by *correlating* the received signal with the locally generated spreading code of the desired user. If the signal matches the desired user's code, then the correlation function will be high and the system can extract that signal. If the desired user's code has nothing in common with the signal, the correlation should be as close to zero
- The spreaded signal (chip) has a much higher data rate (bandwidth) than the original data, and thus CDMA is essentially a form of spread-spectrum technology.

Random Access Technology

- Each user has the right to access the medium without being controlled by any other controller.
- **Access conflict – *collision***: signals will be either destroyed or polluted.
- ALOHA random access: allows mobile users to initiate their transmissions at any time.
  - If a collision occurs, a mobile user will wait for a *random* time and then try resending the data.
- Carrier sense multiple access (CSMA): a mobile user checks the existence of other users' signals before transmitting on a shared transmission medium.
  - Each user tries to detect the presence of radio waves from other users before attempting to transmit its own data.
  - "sense before transmit" or "listen before talk."

Wireless Networks

- Depending on the *transmission range or coverage area*:
  - wireless personal area network (e.g., IEEE 802.15 Bluetooth)
  - wireless local area network (e.g.,IEEE802.11WiFi)
  - wireless metropolitan area network (e.g., IEEE 802.16 WiMAX)
  - wireless wide area network (e.g., IEEE 802.20 MobileFi, and 3GPP Cellular)
  - and wireless regional area network (e.g., IEEE 802.22)
- Depending on the *access and networking technologies*:
  - wireless cellular network
  - wireless adhoc network
  - wireless sensor network
  - wireless mesh network
  - cognitive radio network

Wireless Cellular Network

- A wide geographic area to be covered by radio services is divided into regular shaped zones called *cells* (hexagonal, square, circular or some other regular shapes)
- Each cell is associated with a fixed-location transceiver: Base Station (BS) - located in the center of the cell. Mobile cellular users are connected with each other via the base stations
- Mobile cellular users can move between cells: handoff and mobility management
- To **avoid the interference** from signals from other cells, the adjacent neighboring cells are usually operated on different frequency bands
- To **improve the spectrum efficiency**, the same frequency band is usually used by multiple cells as long as these cells are far enough apart such that the radio signal of one cell does not cause harmful interferences on other cells: ***frequency reuse***
  - Mobile phone network, e.g., global system for mobile communications (GSM), general packet radio service (GPRS), enhanced data rates for GSM evolution (EDGE), and universal mobile telecommunications system (UMTS)
- Most of these cellular systems are based on the 3GPP standards.

Wireless LAN Network

- WLAN is usually used to provide high-speed radio service in a local small area.
- Architecture alternatives:
  1. An infrastructure-based controller: *Access Point (AP)* - connected to a wired network for receiving incoming and sending outgoing traffic.
     - Mobile users communicate with each other or connect to the wider Internet via these APs.
  2. *Ad-hoc network*, where each mobile user transmits data to another user directly
- The coverage area of WLANs is usually small: fewer than 200 meters for each access point
- Mobility of mobile users in a WLAN is rather limited
- Very popular today due to its ability to provide high-speed communication service
- Most of the smartphones, pads, and laptops are equipped with the WLAN interface
- Most modern WLANs are based on the IEEE802.11 standard, marketed under the Wi-Fi brand name

Wireless Ad-hoc Network

- Type of decentralized wireless network, usually based on the IEEE 802.11 standard
- Does not rely on the preexisting infrastructure such as the base station in a cellular network or the access point in a WLAN
- Limited transmission range of mobile nodes: a source node may need to communicate to a destination node in a *multi-hop* fashion
- Each node participates in routing by forwarding data for other nodes, and the decision of which nodes forward data is made dynamically based on the network status
- The network topology changes rapidly and unpredictably over time: nodes need to self-organize to establish network connectivity to support various mobile applications
- Applied to emergency situations like natural disasters or military conflicts due to the minimal need of configuration and quick deployment
- The presence of dynamic and adaptive routing protocols enables an ad-hoc network to be formed quickly.

Wireless Sensor Network

- Consists of a set of spatially distributed autonomous sensors
- Designed to monitor physical or environmental conditions (e.g., temperature, sound, and pressure), and to cooperatively deliver their measured data to a specific location called the *sink node*
- Modern sensor networks are usually bi-directional: they cannot only collect data from sensors passively, but also actively control these sensors
- Primarily motivated by military applications such as battlefield surveillance
- WSNs have been used in many industrial and consumer applications, such as industrial process monitoring and machine health monitoring.
- **Energy constraint**
  - sensors are usually hardware-constrained (small size and low cost), with limited capacity of energy storage (e.g., battery)
  - Hard to charge sensor nodes online and in real-time
- Energy resource, in addition to the radio resource, becomes a very important factor in designing wireless sensor network protocols.

Wireless Mesh Networks

- Radio nodes organized in a mesh topology. Two kinds of different nodes:
  - Mesh clients: laptops, cell phones, and other wireless devices, which transmit/receive data to/from other clients or the wider Internet
  - Mesh routers: stationary nodes such as base stations or access points, which forward a mesh client's traffic to/from other clients or the gateways which connect to the Internet
- Built upon various wireless technologies: IEEE 802.11, 802.15, 802.16, and cellular technologies.
- IEEE 802.11-based wireless mesh network: APs act as mesh routers, and form a mesh backbone for relaying the traffic of mobile users (i.e., mesh clients)
- Special case of the wireless ad-hoc network: mesh routers may be mobile nodes themselves in an ad-hoc network, and can be moved according to specific demands arising in the network
- Mesh routers are not limited in terms of resources compared to other nodes in the network, and thus can be exploited to perform more resource intensive functions.

Cognitive Radio Network

- Novel network architecture based on advanced wireless technologies, e.g., cognitive radio and dynamic spectrum access
- Adaptive, intelligent radio technology that can automatically detect available frequency bands in a certain frequency range
- Enables devices to access the frequency bands distributed in a wide frequency range
- Uses a number of technologies
  - adaptive radio where the communications system monitors and modifies its own performance
  - software defined radio (SDR) where traditional hardware components including mixers, modulators, and amplifiers have been replaced with intelligent software.
- Dynamic spectrum access: allows unlicensed devices to access the frequency bands (licensed to other licensees) in an opportunistic manner, whenever such a secondary access does not generate harmful interference to the licensees
  - spectrum sensing techniques
  - alternative solution: a centralized third-party database called *geo-location database* maintains the up-to-date spectrum usage information of licensees, and can identify the available frequency bands at a particular time and place for secondary access.

Radio Resource Management

- Provides the system level control of interference, efficiency, and other transmission characteristics in wireless communication systems
- Involves strategies and algorithms for controlling network parameters such as transmit power, channel allocation, data rates, handover criteria, modulation scheme, error coding scheme, etc.
- *Objective:* utilize the limited radio spectrum resources and radio network infrastructures as efficiently as possible
  - Power control
  - Channel allocation
  - Admission control

Power Control

- Power control is the intelligent selection of transmit power so as to achieve a good system performance (e.g., low mutual interference, high network capacity, and wide geographic coverage area)
- Widely used in wireless cellular networks, sensor networks, wireless LANs, etc.
- Particularly important for a CDMA system, where multiple mobile users send information simultaneously over a single frequency channel using different spread codes
- Efficient utilization of the energy resource, effectively reduce the mutual interferences between mobile users
- Important for a cellular network based on the FDMA technology (e.g., GSM, GPRS, and EDGE). Mobile users within the same cell may generate interference to users in other cells due to frequency reuse.
- Joint control of users' (or cells') transmit powers is important to further reduce the interference and improve the network performance.

Channel Allocation

- Required to allocate frequency bands (or channels) to base stations, access points, and mobile devices
- *Objective:* achieve a high spectrum efficiency by means of frequency reuse, under the constraints of co-channel interference and adjacent channel interference among nearby cells or networks that share the spectrum band
- Fixed Channel Allocation (FCA): each cell is given a pre-determined set of channels
  - traffic congestion in some cells, while a waste of resource in other cells
- Dynamic Channel Allocation (DCA): cells request channels dynamically based on their real-time traffic load
  - Number of channels in a cell to vary with the traffic load
  - achieve a higher network capacity
- *Sub-channel allocation* problem in an OFDMA system (e.g., 4G cellular network)
  - each mobile user is assigned to a sub-carrier or a sub-channel (i.e., a group of sub-carriers) for their transmissions
  - the same sub-channel may have different wireless characteristics (e.g., channel responses) for different users
  - Ideally, every sub-channel will be allocated to a mobile user who has a good channel response on this sub-channel (*multiuser diversity*)

Admission Control

- Important for wireless communication systems, especially those with limited resources but many potential users
- A conservative admission control policy may reject too many users and result in the under-utilization of radio resources
- Used to differentiate mobile users according to their QoS requirements
    - voice call traffic usually has a strict QoS requirement (e.g., delay and bandwidth)
    - data traffic usually has a more flexible QoS requirement
    - voice traffic may be admitted with a higher priority than data traffic when the network is congested